INFERRING ATMOSPHERIC TURBULENCE STRUCTURE USING SYNTHETIC APERTURE RADAR IMAGES OF THE OCEAN SURFACE

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LONG-TERM GOAL:

My long-term goal is to learn how to remotely sense the properties of the marine atmospheric boundary layer, including mean wind speed and direction, the depth of the boundary layer, and the spatial distribution of atmospheric turbulence, using at least synthetic aperture radar (SAR).

SCIENTIFIC OBJECTIVES:

The objective for this year was to begin the analysis of a data set made up of simultaneous in situ turbulence measurements and SAR imagery. With this data set I can test the hypothesis that radar backscatter from the ocean surface can image atmospheric turbulence and boundary-layer properties. This work is funded by ONR Marine Meteorology and Space and Remote Sensing.

APPROACH:

My approach includes SAR image analysis (for extracting hypothetical atmospheric-turbulence signatures) and time-series analyses. The analysis of time series includes "quadrant analysis" using various definitions of the mean flow, spectral analysis, and various moving operations. Bernie Walter of Northwest Research Associates arranged for the simultaneous capture of the SAR image and in situ turbulence data. Harry Stern of APL has been doing the bulk of the image processing and turbulence data analysis. Chris Vogel of NOAA, who was involved in the acquisition of the turbulence data, has also helped with turbulence-data analysis.

WORK COMPLETED:

The work completed includes SAR image analysis (figure 1), identification in the time series of roll-vortex signatures (figure 2), analysis of temporal variations in temperature profiles (figure 3), and completion of preliminary quadrant analysis which includes

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correlation of gust microfronts with roll vortices (figure 4). Also completed is an analysis of the averaging length necessary to get a convergent value for the mean backscatter from the ocean surface and its comparison with the averaging length necessary to get a convergent mean wind speed in the same place as the backscatter (figure 5).

RESULTS:

A summary of the results is as follows. Figure 1 shows the hypothetical signatures of atmospheric roll vortices in the radar backscatter patterns from the ocean surface. (Note that Bernie Walter has used a different analysis of the same SAR image to successfully identify roll vortices.) Figure 2 shows roll vortex signatures in the time series that are of comparable scale to the hypothetical signatures in the SAR image. (Note that Bernie Walter has used a different analysis of the same time series to successfully identify roll vortices.) Taken together, this is the first definitive correlation of in situ and SAR signatures of roll vortices. Figure 3 shows that this boundary layer's height is temporally varying: in particular there is a strong subsidence event. This means that in order to learn how to extract inversion-layer depths from SAR images based on the spacing of the roll-vortex signatures, one must take into account and correct for the possibility of significant temporal variations in boundary-layer structure. Figure 4 shows the distribution of small-scale turbulence and its correlation with large-scale turbulence (that is, due to roll vortices). This shows for the first time in a definitive way the modulating influence of large-scale turbulence on the spatial distribution of gust microfronts. Figure 5 shows the length scales required to get a convergent mean radar backscatter from the SAR image of Figure 1. This length scale is similar to that necessary to define a convergent mean wind from simultaneous in-situ wind fields.

IMPACT/APPLICATION:

The impact of this work is as follows. If this preliminary work bears fruit, then we can argue that SAR images can be used to remotely sense the instantaneous spatial distribution of atmospheric turbulence over the ocean. Also, it may be prudent to have simultaneous rapid-scan GOES cloud images and SAR images if one wants to infer boundary-layer height remotely because of the possibility of subsidence.

TRANSITIONS:

Transitions of this work in the short-term are likely to be manifest in the work of Ted Rogers (of NRaD in San Diego) who wishes to learn how to relate the spatial patterns of high-grazing angle radar backscatter from the ocean surface to low-grazing angle radar backscatter from the ocean surface (the latter often being called "clutter").

RELATED PROJECTS:

In addition to the work of Ted Rogers, a closely related project includes my recently funded study by the National Science Foundation to look at the signature of atmospheric turbulence over Lake Michigan in simultaneous SAR imagery and in situ turbulence measurements.

REFERENCES:

Besides a Physics of Fluids paper which has recently been re-submitted, I am in the process of writing up the results summarized in the figures of this report. One of the papers (based on combining figure 1 and figure 2) will be done with Bernie Walter, with Bernie as first author. In a separate paper under construction with Chris Vogel and Tim Crawford, I will explore the relationship between large eddies and gust microfronts as manifest in SAR images and concurrent in-situ measurements. I would like to also write up a comparison of the statistics of radar backscatter and in-situ wind fields. Finally, this work will form the basis of initializing a large-eddy simulation of this boundary layer based only on remotely-sensed data.

Figure one: **A SAR image of the ocean surface during the ONR/MBL-ARI**. The image measures 50 km to a side. The straight dark lines show the flight track of the NOAA LongEZ aircraft, whose turbulence data is shown below. The streaks from upper left to lower right are the signatures of atmospheric roll vortices in the oceanic surface-roughness patterns that are imaged by the SAR. Their spacing is on the order of 600 - 1000 m, about twice the height of the boundary layer at the time of the image, and they are oriented within five degrees of the surface-layer wind.

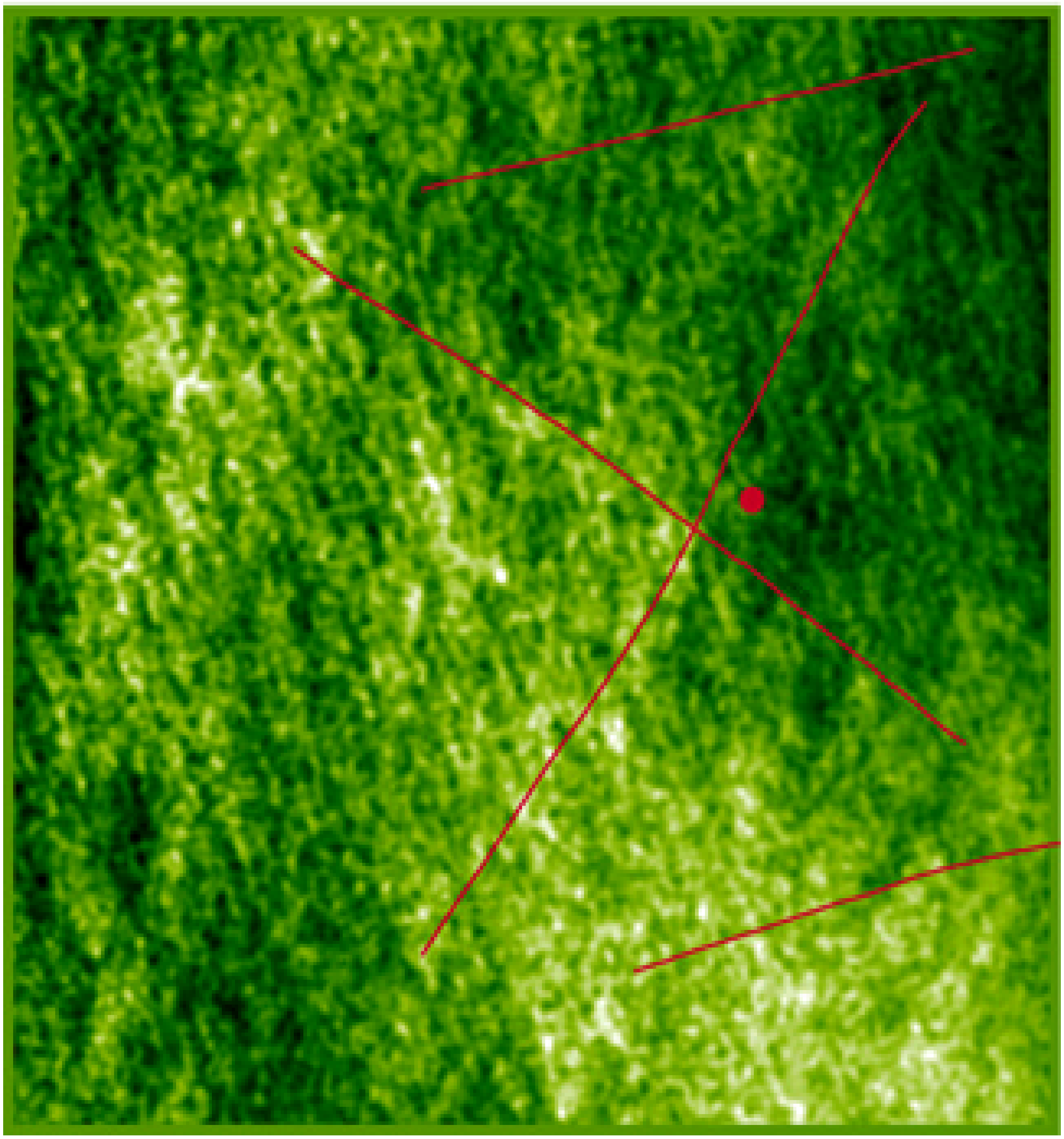

Figure two: **Signatures of roll vortices in in-situ time series of atmospheric turbulence.** The top line shows the perturbation to the mean flow (defined by a five-second running mean, represented by the undulating solid line in this part of the figure) which contains the signature of roll vortices: negative values correspond to low-momentum air within roll-vortex updrafts; positive values correspond to high-momentum air within roll-vortex down drafts. The second line shows the five-second running mean of the cross-wind divergence. Positive values show areas of divergence (indicative of the bases of down drafts); negative values show areas of convergence (indicative of the bases of updrafts). Convergence/divergence regions are lag-correlated with low-/high- momentum regions. The third and fourth lines show the instantaneous vertical and cross-wind velocities, respectively, with their five-second running means.

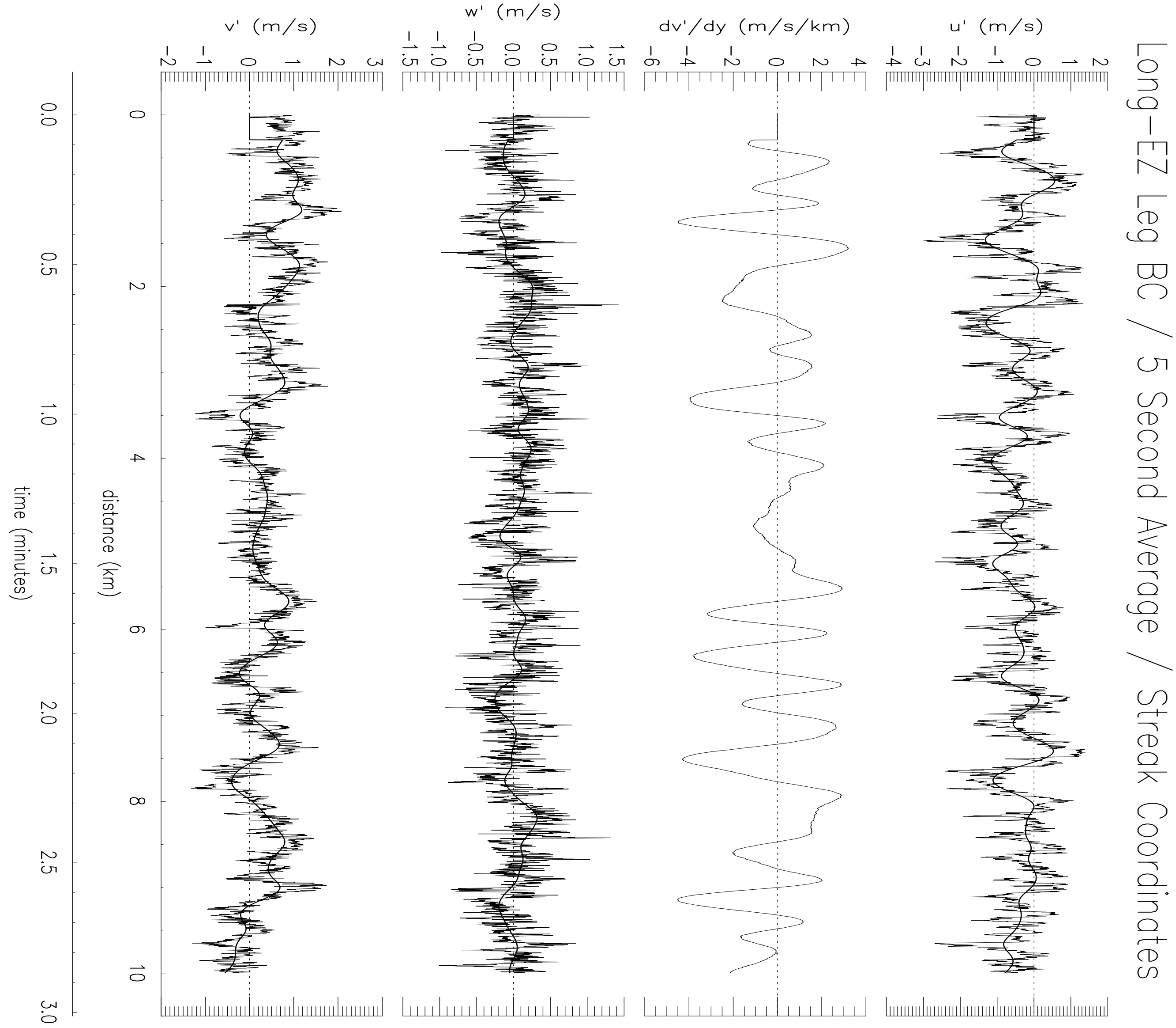

Figure three: **Vertical profiles of atmospheric temperature** captured at the times indicated at the top of the profiles. The pairs at each time are associated with aircraft descents and ascents**.** The sharp kink in the profiles (at about 730 m in the first profile, for example) gives a measure of the inversion height. The figures demonstrate that there was significant subsidence during the experiment. The SAR image was captured during the peak of the subsidence, between 18:16 and 19:18 Universal Time, when the boundary-layer height changed from about 700 m to 375 m.

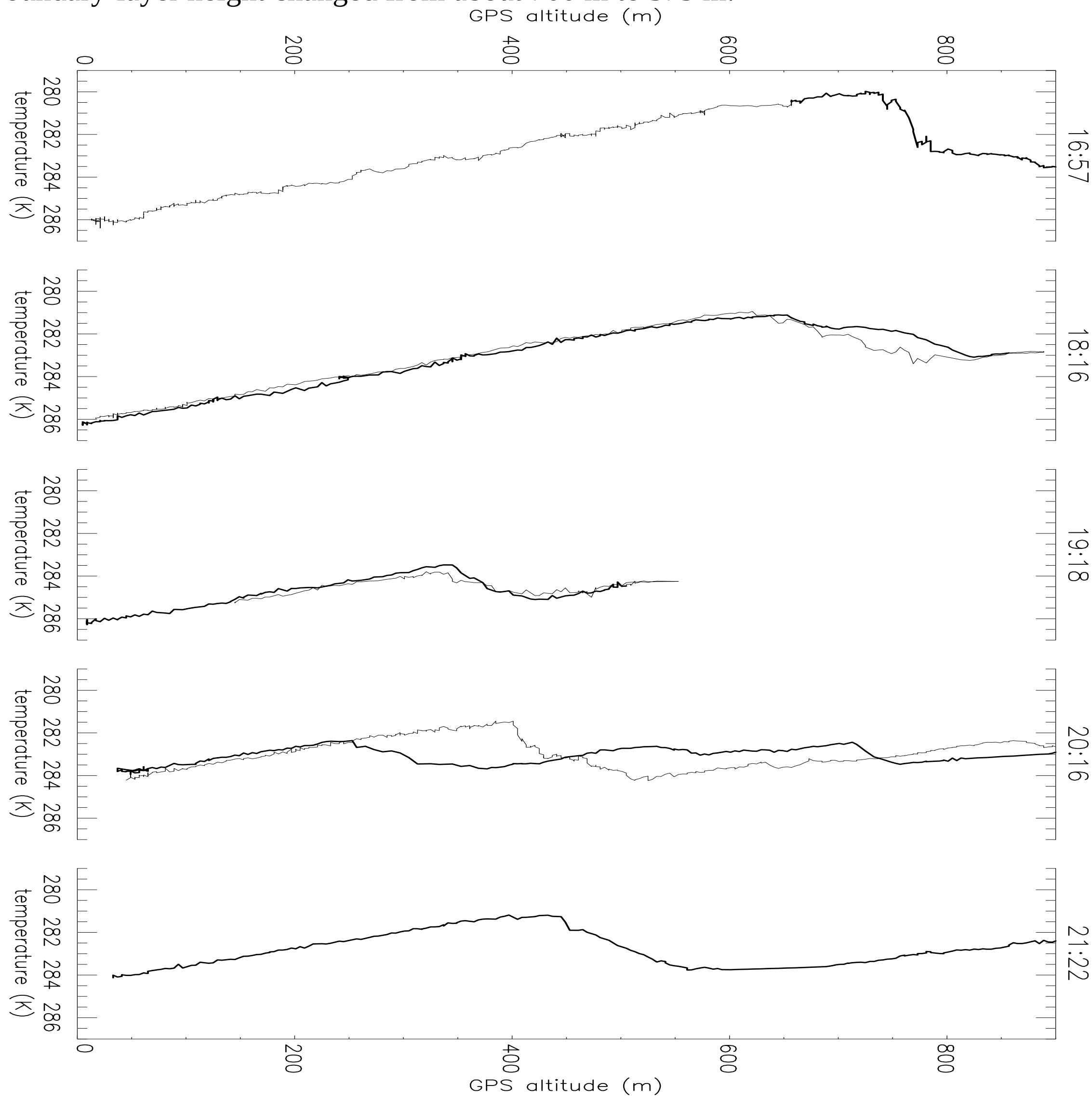

Figure four: **Preliminary quadrant analysis**. The first and second lines show the instantaneous wind components (along-wind and vertical wind components, respectively) relative to a twenty-second running mean. The third line shows their product: the instantaneous Reynolds stress or momentum flux caused by both roll vortices and smaller-scale turbulence. Using a “quadrant analysis” technique that identifies the significant momentum flux events, the bottom line shows a grouping of them within two categories: ejections (upward momentum-flux events) and sweeps (down ward momentum-flux events). The ejections are primarily within the roll-vortex updrafts and the sweeps are primarily within the roll-vortex down drafts. Indeed, the spacing between groups of ejections or groups of sweeps is the same as between roll updrafts and down drafts, respectively. This small-scale turbulence, modulated by the roll vortices, is what actually roughens the ocean surface in a way that can be imaged by SAR.

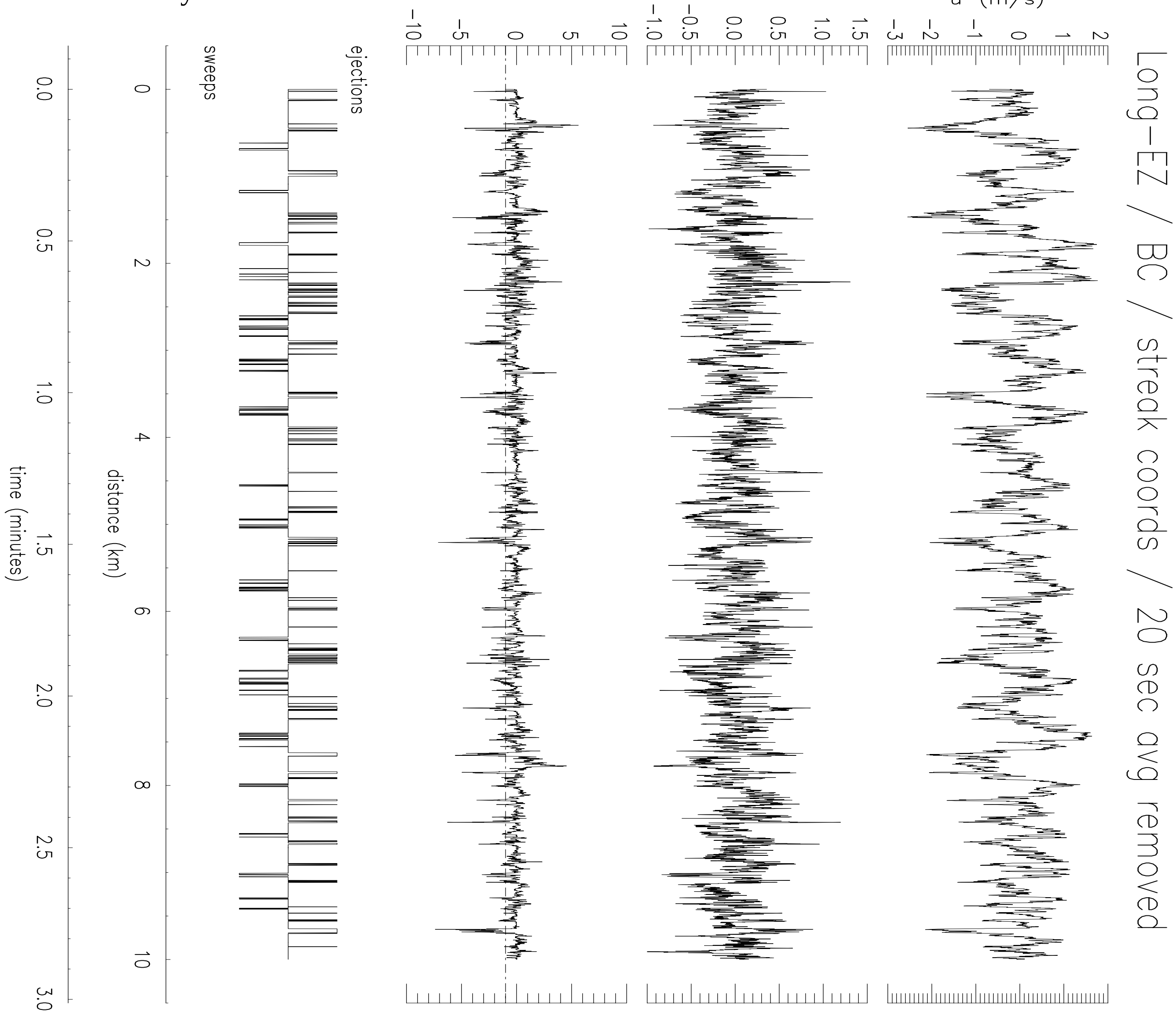

Figure five: **Radar-backscatter averaging length as a function of position across radar-backscatter streaks**. If the radar backscatter patterns are caused by atmospheric turbulence, length scales extracted from various statistical measures applied to each of the backscatter fields and turbulence fields should be comparable. Shown here are two bounds on the convergent running mean of radar backscatter cross-section taken from the SAR image of Figure one. This running mean is calculated along lines that are perpendicular to the axes of the SAR streaks shown in Figure one. The majority of the length scales that define a convergent mean radar backscatter range from two to six kilometers. Cross-roll aircraft flights can measure the mean wind in the same way that I have just calculated the mean radar backscatter. Using the same criterion for convergence for the mean wind as for the radar backscatter, the resulting length scales (with far fewer realizations, unfortunately) are of comparable size to the length scales required to construct a convergent mean radar backscatter value. This is consistent with the hypothesis that the radar backscatter patterns are caused by atmospheric turbulence.